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Thermal behaviour of additively manufactured injection moulding inserts

Thomas Hofstätter[1*], David B Pedersen[1], Guido Tosello[1], Hans N Hansen[1]

[1]*Technical University of Denmark, Department for Mechanical Engineering*

** Corresponding author: thohofs@mek.dtu.dk*

Abstract
Injection moulding using inserts from vat polymerization, an additive manufacturing technology, has been investigated for pilot production and rapid prototyping purposes throughout the past years. Experiments have used a standard mould is equipped with additively manufactured inserts in a rectangular shape of (20 x 20 x 2.7) mm^3 produced with vat photo polymerisation. While the lifetime compared to conventional materials such as brass, steel, and aluminium, is reduced, the prototyping and design phase can be shortened significantly by using flexible and cost-effective additive manufacturing technologies. While crack propagation has been significantly reduced, further developments become possible, such as multi-scale injection moulding inserts with dimensions of (80 x 60 x 10) mm^3 where an insert with larger outside dimensions and micro features on the surface is used during the manufacturing process.
Higher manufacturing volume still exceed the capability of additively manufactured inserts, which are overruled by the stronger performance of less-flexible but stronger materials. This contribution discusses the heat transportation within the inserts made from a thermoset material, brass, steel, and ceramic material. It therefore elaborates on the possibilities of injection moulding as well as the thermal challenges connected with the use of polymer inserts. They are an essential part for further calibrations of the injection moulding process.

Keywords: Additive Manufacturing, Injection Moulding, Micro Structures, Inserts, Simulation

1. Introduction

Challenges of injection moulding (IM) pilot production are located in the high costs and long prototyping cycles. Additively manufactured (AM) inserts were introduced in order to face these challenges in rapid prototyping (RP) and pilot production.

Over the past years, several scientific investigations have been conducted in order to improve the lifetime of AM IM inserts starting from the elementary manufacturing without reinforcement based on vat polymerisation (VP) processes of photopolymer (PhP). [1] Proposed development steps are illustrated in Figure 1 whereas step 1 and step 2a for inserts with dimensions of (20 x 20 x 2.7) mm^3 were already experimentally investigated and showed a statistically reproducible lifetime improvement by a factor of 10. [2, 3]

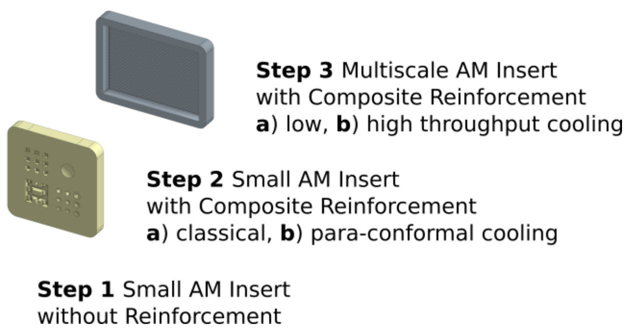

Figure 1. Development steps of IM inserts. a) and b) represent substeps and refinements of the development step.

Further developments shown in step 3 include the advancement of the IM inserts into multiscale in the cm-range using the advantage of VP of producing micro-features without further processing complexity. All of the development steps were covered in numerical simulations for multiple IM cycles predicting challenges and possibilities of further development steps.

2. Methods

The numerical simulations were conducted using the Comsol Multiphysics® version 5.3 Modules for laminar fluid flow and heat transfer as well as the multiphysics model for non-isothermal flow. Materials were chosen according to Table 1: PhP, brass, steel, silicon carbide (SiC).

The interface between the flowing and cooling injected material acrylonitrile butadiene styrene (ABS) was approximated by applying effusivity between the materials according to the following equations (all units were considered according to SI):

$$T_i = \frac{b_1 T_1 + b_2 T_2}{b_1 + b_2}$$

$$b_i = \sqrt{k_i \rho_i c_{pi}}$$

Whereas
T ... *Temperature at interface*
k ... *Thermal Conductivity*
ρ ... *Density*
c_{pi} ... *Heat capacity*

Table 1 Part materials, development steps and interface temperature.

Part	Material	Steps	T_i with ABS
Conventional Mold	Steel	1-3b	32.2 C
Insert	PhP	1-3b	121.0 C
	Brass	1-3b	30.0 C
	Steel	1-2b	32.2 C
	SiC	1-2b	27.4 C
Injected Material	ABS	1-3b	n/a
Cooling Fluid	Water	2a-3b	n/a

The cycle was considered as 1.5 s injecting, 7 s packing, 11.5 s mould opening and natural cooling adding up to a cycle of 20 s. The fluid flow was approximated as constant during the entire cycle with 5 l/min (development steps 2a, 2b, 3a) and 10 l/min (development step 3b, high throughput (HT)). The surrounding temperature was approximated with 25 C in infinity. The fluid cooling was considered with a constant inlet temperature of 15 C over the entire cycle. Surfaces were cooled by natural convection when exposed to the surrounding.

3. Results

The high interface temperature due to the effusivity of the PhP, cooling required a higher heat transfer into the mould and surrounding visualised in Figure 2. The conventional mould showed only slight temperature increase whereas it needs to be considered that the overall heat capacity of the steel mould is significantly greater than the inserts. An influence of the inserts on each other was therefore not detected which allows for further prototyping techniques, e.g. a reference insert while the other inserts are changed during the prototyping development.

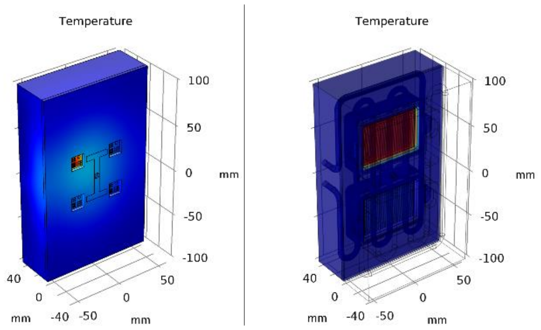

Figure 2. Temperature of one mould side. The right figure shows transparent features in order to see the cooling system.

In all development steps, the PhP insert showed significantly higher temperatures (Figure 3) which can be explained by the higher interface temperature as well as smaller conductivity of the polymer. Moreover, the interface between the inserts and the conventional mould allows a higher heat transfer when pairing two metals, as they are not welded.

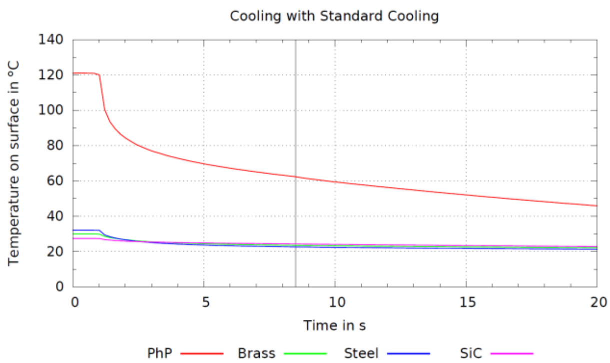

Figure 3. Cooling of the surface of the insert with standard cooling. Ejection of the moulded part after 8.5 s.

Figure 4 and Figure 5 elaborate the potential of development steps 2b-3b. It is also shown that the cooling mechanism in the higher development steps provides a stronger heat transfer. Para-conformal cooling moulds applying the advantages of AM in terms of pressure reduction, e.g. by rounded edges, allow higher throughput of the cooling fluid, which leads to further temperature decrease. This is however not necessary for the metal and ceramic insert materials as their possible cycle time is massively decreased as compared to PhP.

It is moreover shown that an increased absolute heat capacity consequently increases the insert temperature whereas the temperature of the cooled inserts is significantly lower than the temperature for simple para-conformal cooling. The higher absolute heat capacity can therefore be compensated.

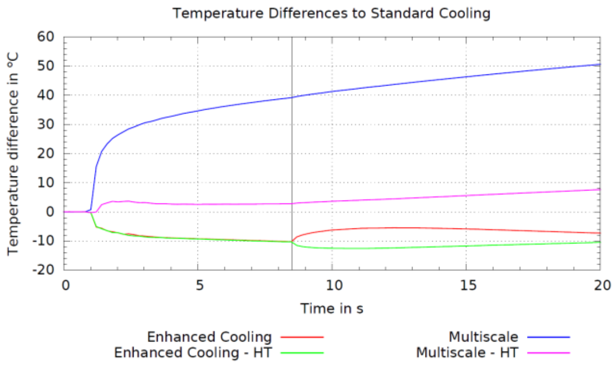

Figure 4. Difference to standard cooling of PhP inserts.

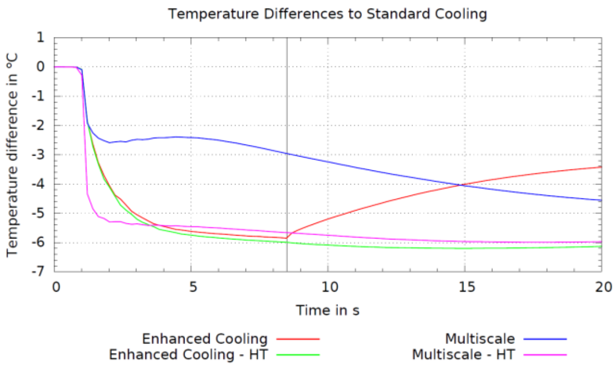

Figure 5. Difference to standard cooling of brass inserts.

Concerning the development step 3 inserts, it will be required to consider thermal stresses in the layers between the cooling channels and the injected ABS material. Prior investigations [3], however, have shown that the crack propagation can be significantly reduced by applying fibre-reinforcement in the VP inserts.

4. Conclusions

Composite reinforcement and fibre-reinforcement of IM inserts have enhanced material properties in a region where multiscale inserts become possible. Advanced cooling techniques such as conformal cooling of the standardized mould, forced convection, or elaboration on the thermal properties of the inserts will need to be considered in order to reduce the influence of effusivity on the IM process.

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